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Neutrino Flux Studies at NO ν A

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We present the systematic-error study of the neutrino flux in the NO ν A experiment. Systematic errors on the flux at the near detector (ND), far detector (FD), and the ratio FD/ND, due to the beam-transport and hadro-production are estimated. Prospects of constraining the ν_μ and ν_e flux using data from ND are outlined.

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1 Introduction

The NuMI Off-axis ν_e Appearance (NO ν A) experiment is composed of two functionally identical detectors. NO ν A is designed to address a broad range of open questions in the neutrino sector through precision measurements of $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ oscillations including neutrino mass hierarchy, CP violation in the neutrino sector. To minimize the systematic errors, a functionally identical Near Detector (ND 0.3kt) is placed close to the neutrino source, while the far detector (FD 14kt) is located 810km from the source, observes the oscillated beam. For all of the oscillation measurements, NO ν A takes advantage of a two-detector configuration to mitigate uncertainties in neutrino flux, neutrino cross sections, and event selection efficiencies. NO ν A uses Fermilab's NuMI beam line as its neutrino source. This paper focuses on the estimating the systematic errors on the NO ν A flux, and constraining these errors using the ND-measurements.

2 Detectors

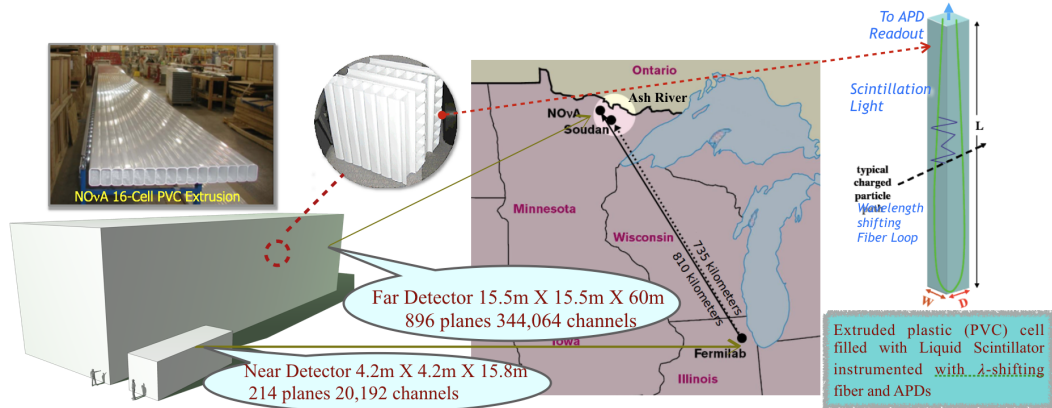


Figure 1: NO ν A detectors, with a human figure shown for scale. The FD differs from the ND only in the length of its PVC cells and the number of layers present.

The NO ν A detectors are situated 14 mrad off the NuMI beam axis, so they are exposed to a relatively narrow band of neutrino energies centered at 2 GeV. The NO ν A detectors are largely active (65%) and highly segmented detectors composed of low-Z tracking calorimeters. The segmentation and the overall mechanical structure of the detectors are provided by a lattice of PVC cells, as shown in Figure 1. The dimension of the PVC cells is $4 \times 6 \text{ cm}^2$. Each layer is 0.15 X_0 (radiation-length) thick. Each plane is composed of individual cells instrumented with 1-sided readout using

avalanche photodiodes (APD). Each layer in the detectors is oriented orthogonally to adjacent ones to provide 3D event reconstruction, a cut-away view of the PVC cellular structure. The ND(FD), where the cells are 4.2 m (15.5 m) long, is composed of 192 (896) planes.

3 NuMI Beam Line

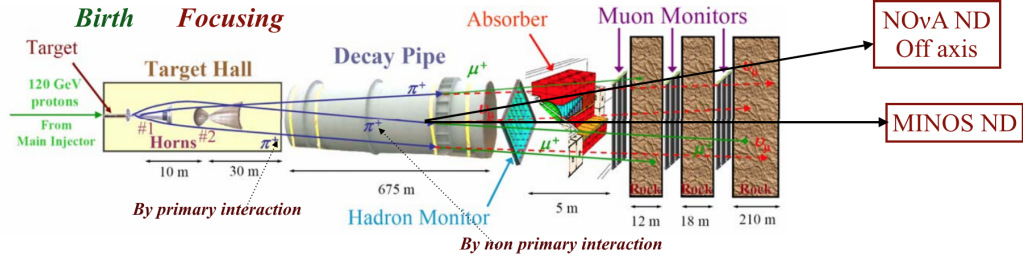


Figure 2: Schematic of the NuMI Beam: Shown are the primary proton-C collision, the π^+ , π^- , K^+ , K^- , and K_L^0 mesons that are the primary progenitor of neutrinos, the focusing beam elements, and secondary/tertiary sources of neutrinos.

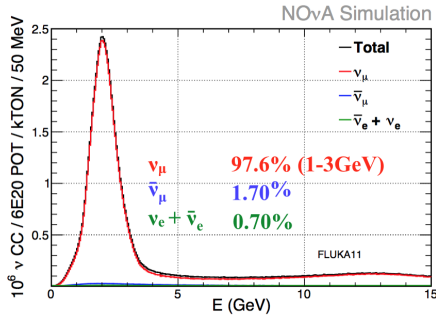


Figure 3: ν mode: horns focus positives

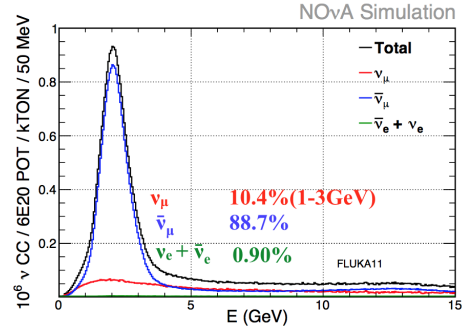


Figure 4: $\bar{\nu}$ mode: horns focus negatives

The schematic of the NuMI beamline is shown in Figure 2. A 120 GeV proton-beam from the Main Injector is impinging upon a graphite target. Secondary particles produced from the p-C interaction are focused by two horns where a strong magnetic field is present. Of all these secondary particles, most important are pions and kaons, because they are the dominant source of neutrinos. After being focused, they are left free to decay in a decay pipe. At the end of the decay pipe, the hadrons are absorbed

in a hadron-absorber[1]. Due to Off-axis position of detector, the beam is rich in pure ν_μ in neutrino mode as shown in Figure 3 and $\bar{\nu}_\mu$ in the antineutrino mode, see Figure 4.

4 Motivation for the Beam-Systematics

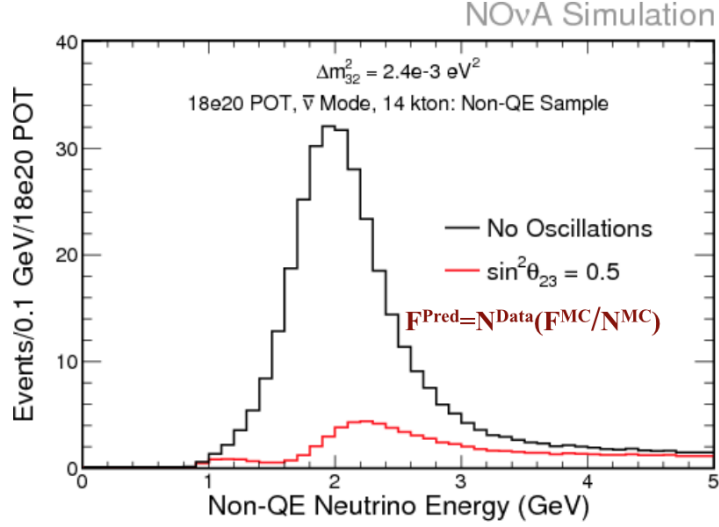


Figure 5: Oscillated and Un-Oscillated spectrum at FD

The sensitivity of the oscillation studies critically depends upon the precise prediction of the ratio of the unoscillated to oscillated flux, ν_μ , $\bar{\nu}_\mu$, $\nu_e + \bar{\nu}_e$ in $\text{FD}/\text{ND}(E_\nu)$ as shown in Figure 5. Uncertainties in FD/ND come from the proton-nucleon hadro-production and the beam transport simulation. Needed are data-driven methods to constrain the uncertainties. The most important data are the NOvA-ND data. Other constraints include MINOS, NDOS (Near Detector Prototype On Surface) data, and the hadro-production data (MIPP, NA49...)[2].

5 Beam systematic uncertainties

Neutrino flux prediction based solely upon MC is not precise. Large uncertainties associated with the proton-nucleon hadro-production processes in primary and secondary/tertiary targets induce a large uncertainty ($\approx 20\text{-}25\%$) in the neutrino flux. However measurements and discoveries of the elements of the neutrino mixing matrix critically depend upon the precision with which one can predict the neutrino flux

ratio at the far detector (FD) with respect to the near detector (ND) as a function of the neutrino energy (E_ν) and the ν_e/ν_μ flux ratio. Poor measurements of the secondary meson production in p-Nucleus collision, $d^2\sigma/dx_F dp_T$ contribute to the flux error. The mesons include π^\pm , K^\pm , and K^0 , produced in the 120 GeV p-C collision. Additional errors are due to the beam-transport simulation. Beam Simulation is based upon FLUGG 2009.4 Flugg 2009-3d[3] and Fluka (2011.2b.6) as standard Monte Carlo.

5.1 Beam Transport Systematics

This study includes variations in parameters associated with the beam transport and presenting the variations in the flux at ND, FD, and (FD/ND) as a function of neutrino energy[4][5]. For the beam simulation, the nominal parameters are: Flugg 2009-3d and Fluka (2011.2b.6), Forward Horn Current, nominal Horn Current 200kA, linear BField distribution. Beam spot size 1.1mm, PEANUT generator turned on for all energies[6].

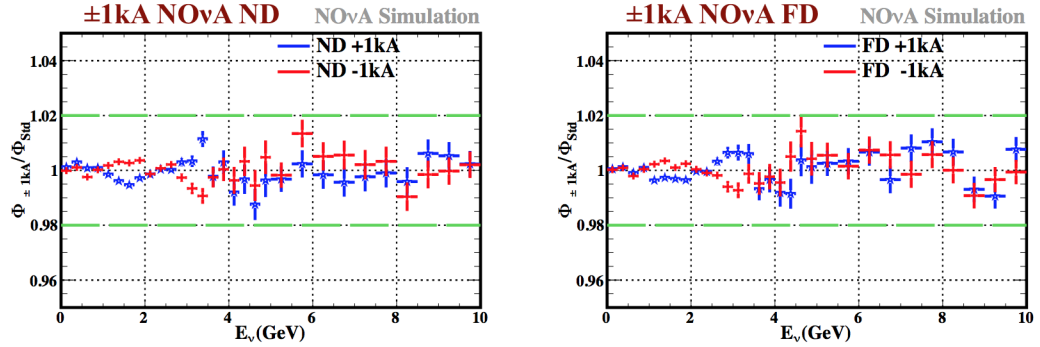


Figure 6: Left: ratio of ν flux with variants, $\pm 1\text{kA}$ shift, blue (+1kA) and red (-1kA), to nominal ν flux (200kA) at NO ν A ND. Right: ratio of ν flux with variants, $\pm 1\text{kA}$ shift, blue (+1kA) and red (-1kA), to nominal ν flux (200kA) at NO ν A FD.).

Flux Systematics Variants for Beam transport: The following variations are considered:

- Horn Current shifted by $\pm \text{kA}$ w.r.t nominal
- Beam spot size shifted by $\pm .2\text{mm}$ both in X and Y w.r.t nominal
- Horn1 & Horn2 position shifted by $\pm 2\text{mm}$ w.r.t nominal
- Target position shifted by $+2\text{mm}$ shift w.r.t nominal
- Beam position on the target shifted by $\pm .5\text{mm}$ in X & Y separately
- B-field modeling changed to an exponential magnetic field (0.77cm skin depth) in the horn skin.

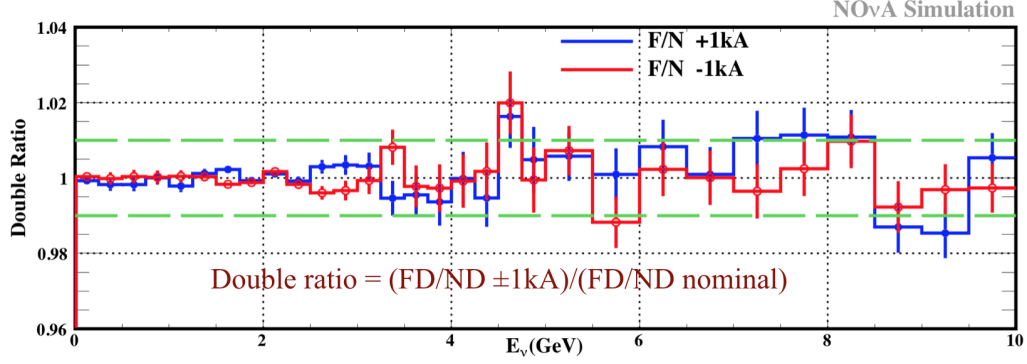


Figure 7: Double-Ratio $\frac{\Phi_{FD/ND(variant)}}{\Phi_{FD/ND(Std)}}$ for +1kA shift (blue) and -1kA shift (red)

Table 1: $\delta(\%)$ ν_μ and Energy(Mean and RMS) at NO ν A ND (1-3)GeV

Shift	$\delta(\%)$ at ND	$\delta(\%)$ at FD
Std	0.00	0.00
+1kA Horn Current	-0.20	-0.16
-1kA Horn Current	0.16	0.10
Horn1 +2mm X & Y	-0.44	-0.39
Horn1 -2mm X & Y	-1.70	-1.76
Horn2 +2mm X &	-0.51	-0.47
Horn2 -2mm X & Y	0.37	0.30
Exp Magnetic Field	-4.30	-4.32
BmPosX 0.5mm	-0.66	-0.68
BmPosX -0.5mm	0.26	0.24
BmPosY 0.5mm	0.13	0.18
BmPosY -0.5mm	-0.35	-0.45
BmSpotSize +0.2mm X & Y	-0.77	-0.81
BmSpotSize -0.2mm X & Y	0.29	0.29
TarPos +2mm in Z	-0.08	-0.09
FTFP_BERT	-3.65	-3.76

In the following we show only one sample flux-error calculation due to the variation in the horn current, shown in Figure 6 and Figure 7. Similar set of calculation is performed for each of the errors listed above. The fractional variations in the yield of ν_μ at ND and FD due to the various error-conditions are presented in table 1[7].

5.2 Uncertainties in hadron production based on NA49 data

One key systematic uncertainty is the uncertainty on the simulation of the production of pions and kaons off the carbon target because the yield and kinematics of the pions and kaons coming off the target can alter the abundance and energy of focused pions and kaons that decay to produce muon and electron neutrinos observed at the NO ν A detectors. The core concept is to vary hadro-production parameters within reasonable limits in a physically justifiable way, to use the shifted hadron production to create shifted-flux distributions, and then use the shifted-flux distributions to generate a covariance matrix. Alternative hadron production parameterizations are created around a best fit (BMPT[8]) to a FLUKA simulation of the NA49 target; the resulting error covers the difference between the Fluka-MC and NA49[9].

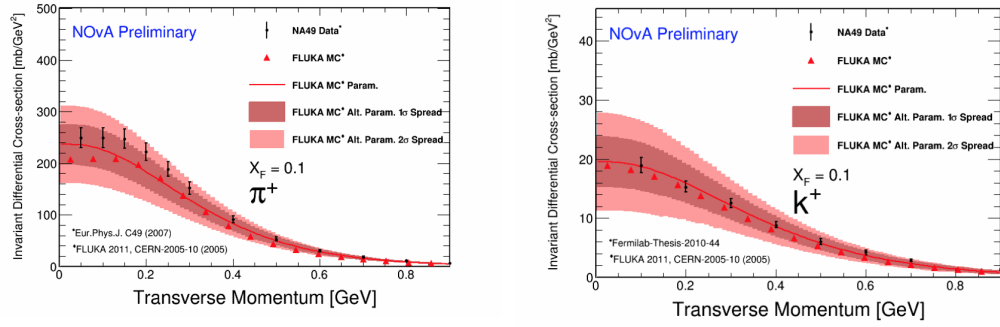


Figure 8: Invariant differential cross section for particular x_F and as a function of p_T for Pions (left) and Kaons (right) produced in p+C collisions at 158 GeV/c beam momentum. Data is shown in solid black, MC in solid light red, the parameterization of the MC as a light red dotted line, and the 1 & 2 sigma spread in alternative parameterizations of the MC is shown as a pair of light red bands.

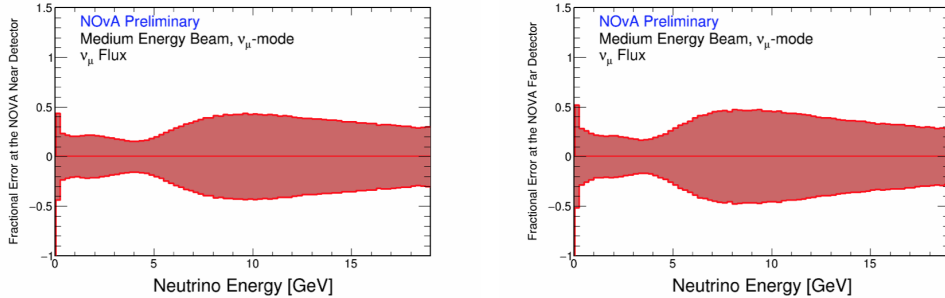


Figure 9: The square root of the diagonal elements of the covariance matrix describing the hadron production uncertainty on the beam ν_μ flux at the ND and FD.

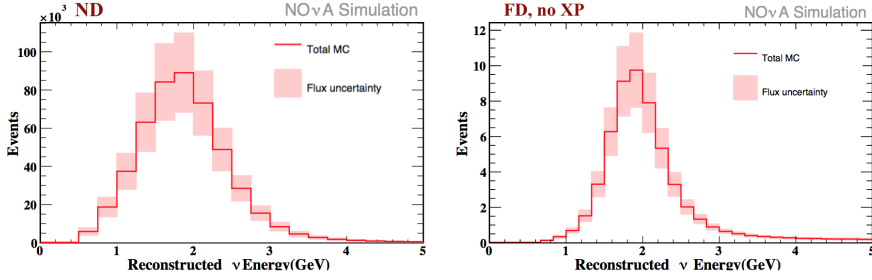


Figure 10: The error band represents a 1 sigma shift of all beam systematics: including NA49 Hadroproduction Uncertainty, Spot size, Beam position on the target (X/Y), Target position, Horn current, Horn positions, & the modeling of horn's B-field.

The difference between nominal and shifted parameterizations is used to create weights in P_T and x_F of hadrons produced off the NuMI target, which, then, can be used to re-weight the NOvA Near and Far Detector neutrino spectra, see Figure 8 and Figure 9.

Beam Transport Errors, including NA49 Hadroproduction Uncertainty on Reconstructed neutrino energy[GeV] in NOvA ND & FD for 6e20 POT as shown in Figure 10.

6 Constraints using ND Data

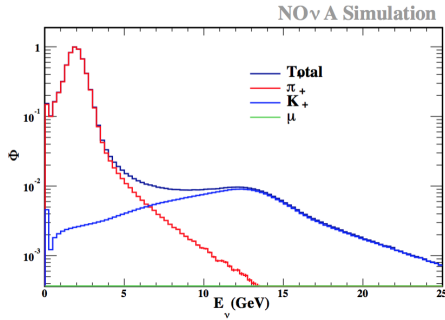


Figure 11: E_{ν_μ} at ND

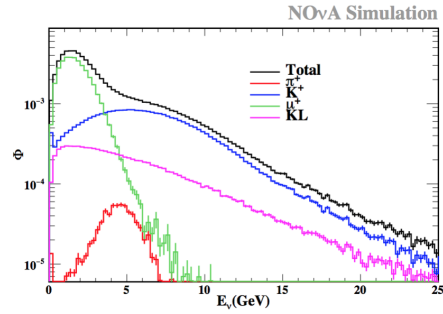


Figure 12: E_{ν_e} at ND

We have shown systematic uncertainties from the beam transport and hadron production. These predictions need to be further constrained by the ND Data. Since 97% of ν_μ at the ND are from $\pi \rightarrow \nu_\mu + \mu$. We plan to use neutrino data in 1-3 GeV to constrain the pion yield, and use $E_\nu \geq 5$ GeV to constrain K^+ yield.

7 Summary:

We present the flux systematic errors arising from the uncertainties in the beam transport & hadro-production MC model. For beam transport parameters $\delta(\%)$ for $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ is $\approx 3\%$ for ND and FD(1-3)GeV, Energy variation for $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e \approx 1\%$ for ND and FD(1-3GeV). Combined uncertainties using hadroproduction with beam transport parameters at ND is $\pm 23.9\%$ and at FD is $\pm 20.9\%$ [7]. The flux prediction can be made more precise by using the constraints provided by the neutrino spectra from ND, as we plan to do in the future.

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